Cloud-free shortwave aerosol radiative effect over oceans: Strategies for identifying anthropogenic forcing from Terra satellite measurements

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[1] Using the Single Scanner Footprint (SSF) data that combines the multi-spectral Moderate Resolution Imaging Spectroradiometer (MODIS) cloud and aerosol products with the Clouds and the Earth's Radiant Energy System (CERES) top of atmosphere broadband radiative fluxes, we first provide observational estimates of the instantaneous cloud-free shortwave aerosol radiative forcing (SWARF) over the global oceans. Different from our previous research, we corrected for both the sample biases and the diurnal cycle of SWARF and the cloud-free diurnally averaged SWARF is -5.3 ± 1.7 Wm^{-2}, a value that is consistent with previous studies. Furthermore, we partition the CERES shortwave flux as a function of MODIS aerosol optical thickness and the fraction of fine mode aerosol to the total aerosol optical depth (η). Since η is related to particle size and is a good surrogate for aerosol type, we present strategies for estimating the radiative forcing of *anthropogenic aerosols* from MODIS and CERES measurements that is important for quantifying the climate forcing of aerosols. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 4801 Oceanography: Biological and Chemical: Aerosols (0305). **Citation:** Christopher, S. A., and J. Zhang (2004), Cloud-free shortwave aerosol radiative effect over oceans: Strategies for identifying anthropogenic forcing from Terra satellite measurements, *Geophys. Res. Lett.*, *31*, L18101, doi:10.1029/2004GL020510.

1. Introduction

[2] Tropospheric aerosols such as smoke from biomass burning, dust, and pollutant aerosols, affect weather, climate and health by reducing visibility, altering the earth's radiative energy budget [*Ramanathan et al.*, 2001], changing cloud formation [*Koren et al.*, 2004], affecting rainfall distribution [*Rosenfeld*, 2000], changing dynamics of circulation patterns [*Andreae et al.*, 2004] and also by inducing respiratory diseases when sub-micron particles penetrate the lungs [*Pope et al.*, 1995]. One of the greatest uncertainties in our current understanding of the climate system is the effect of aerosols on the earth's radiative energy budget and the unraveling of these complex interactions of aerosols within the earth-atmosphere system continues to be a challenge since aerosols have short life times in the atmosphere and have different chemical compositions and properties that are not readily measured on global scales [*Kaufman et al.*, 2002].

[3] Aerosols are usually categorized as natural and anthropogenic, where dust and marine sea salt aerosols from wind driven mechanisms are called 'natural aerosols' and aerosols from biomass burning smoke, industrial and other pollution due to human-induced activities are called 'anthropogenic aerosols'. The widely used method for studying the radiative impacts of aerosols are from global models where the natural and anthropogenic components are separated and the radiative effect of anthropogenic aerosols are called climate forcing of aerosols [*Hansen et al.*, 1998]. The aerosol distributions in global models are prescribed by three dimensional chemistry transport models that compute aerosol distributions from source emissions using prescribed meteorological fields. Although these models can be used to separate the radiative effects of various aerosol fields, considerable uncertainties exist on the spatial and temporal distribution of aerosols and their associated properties [*Haywood et al.*, 1999]. Simpler techniques use a single radiative transfer equation, valid for optically thin aerosols, and estimate the global aerosol climate forcing of various components that also make numerous assumptions [e.g., *Penner et al.*, 1994].

[4] Satellite measurements also play a major role for studying the radiative impact of aerosols [e.g., *Boucher and Tanré*, 2000; *Chou et al.*, 2002] although most of these studies have been confined to the oceanic regions. However, most satellite data sets have limited information for precisely separating the effect of natural from anthropogenic pollution and usually only the combined effect of aerosols have been examined. However, recent studies from the Polarization and Directionality of the Earth's Reflectances (POLDER) instrument show promising results for separating the effect of anthropogenic from natural aerosols [*Bellouin et al.*, 2003] although only limited data is available from this instrument. The aerosol optical thickness retrieved from satellite measurements is centered around narrow wavelength ($\sim$0.1 μm width) intervals and are used in radiative transfer calculations to estimate the radiative fluxes in the entire solar spectrum ($<\sim$4 μm) (e.g., 0.865:POLDER [*Boucher and Tanré*, 2000]; 0.865 μm: Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [*Chou et al.*, 2002]; 0.55 μm: Moderate Resolution Imaging Spectroradiometer (MODIS) [*Yu et al.*, 2004]; 0.64 μm: Geostationary Operational Environmental Satellite (GOES) [*Christopher and Zhang*, 2002b]). During these calculations, the solar spectrum is divided into a discrete number of bands and wavelength dependent aerosols (aerosol optical depth, single scattering albedo, asymmetry parameter) and surface

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(surface albedo) properties are used to calculate the reflected solar flux at the top of atmosphere (TOA). Since the aerosol optical thickness (AOT) is usually available only from one wavelength, assumptions or climatological averages are needed to obtain aerosol properties at other wavelengths [e.g., *Christopher and Zhang*, 2002b].

[5] Another technique that does not require radiative transfer calculations to convert the satellite-retrieved AOT into TOA fluxes utilizes collocated narrowband and broadband instruments from the same satellite platform although these techniques estimate the combined effect of *all* aerosols [*Loeb and Kato*, 2002; *Christopher and Zhang*, 2002a]. In this technique, aerosols are identified, their properties are obtained from multi-spectral measurements such as the MODIS [*Kaufman et al.*, 2002] and the radiative fluxes are obtained directly from the Clouds and the Earth's Radiant Energy System (CERES) measurements, therefore bypassing radiative transfer calculations. The radiative effect of aerosols can be obtained by examining TOA CERES fluxes with and without the presence of aerosols that is called shortwave aerosol radiative forcing (SWARF) [*Christopher and Zhang*, 2002a].

[6] Although this method has the distinct advantage of not requiring the use of radiative transfer calculations to convert the MODIS AOT to TOA fluxes, one major disadvantage is the large size of the CERES footprint. Even if is there is one cloudy pixel within the CERES pixel, as determined by MODIS data, the CERES pixel is usually excluded from the analysis [*Christopher and Zhang*, 2002a]. In comparison, radiative transfer approaches [*Chou et al.*, 2002; *Yu et al.*, 2004] use aerosol products at higher spatial resolution (10 km for MODIS, 1 km for SeaWiFS), although the POLDER product is at a coarser resolution of 20 $\times$ 20 km [*Boucher and Tanré*, 2000; *Bellouin et al.*, 2003]. Therefore sample biases could exist in the MODIS/CERES analysis due to the large footprint of the CERES pixels and also in techniques that utilize coarse spatial resolution aerosol products.

[7] The conversion of the CERES broadband radiances to TOA fluxes is not a disadvantage since empirical methods are available from Terra and Aqua [*Loeb and Kato*, 2002; J. Zhang et al., Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 1. Angular dependence models, submitted to *Journal of Geophysical Research*, 2004a, hereinafter referred to as Zhang et al., submitted manuscript, 2004a]. Another issue that must be addressed is diurnal averaging. The usual approach is to take the satellite derived AOT during the time of the polar-orbiting overpass and convert them to diurnally averaged values. Both the radiative transfer [*Boucher and Tanré*, 2000; *Chou et al.*, 2002] and the satellite-based approaches [*Loeb and Kato*, 2002] must deal with this problem. The radiative transfer methods typically assume that the AOT measured at the time of the satellite overpass is representative of the diurnal cycle [*Kaufman et al.*, 2000] and scale the calculated fluxes by the solar zenith angle. Although the Terra and Aqua retrieved AOT during the time of the satellite overpass is within 2% of the diurnal averages as reported by Aerosol Robotic Network (AERONET) stations [*Kaufman et al.*, 2001], large regional variations from episodic events could affect this assumption that requires further investigation [*Myhre et al.*, 2004].

[8] Since aerosol climate forcing is defined as the effect of *anthropogenic* aerosols (and not the combined effect of all aerosols) on the radiative energy balance there is a need to separate the retrieved AOT and consequently the SWARF into natural and anthropogenic components. *Bellouin et al.* [2003] separated dust and sea salt aerosols from fine mode aerosols (a surrogate for anthropogenic aerosols) by applying thresholds to the Angstrom exponent derived from POLDER measurements to estimate aerosol absorption over cloud-free oceans. More recently, *Kaufman et al.* [2004] distinguished dust from other aerosols by applying thresholds to the fraction of fine mode to the total MODIS AOT over the oceans (η) for studying dust transport and deposition in the Atlantic Ocean. Much like the Angstrom exponent, η is an index of particle size and aerosol type and has the potential for separating natural from anthropogenic aerosols since large η values signify larger fine mode fractions that are largely from anthropogenic aerosols [*Kaufman et al.*, 2002]. Although these methods are sensitive to the applied thresholds and are yet to be fully validated, they provide the framework for separating natural from anthropogenic aerosols from satellite observations for radiative forcing studies.

2. Methods and Results

[9] We use ten months (November 2000–August 2001) of collocated MODIS and CERES Single Scanner footprint (SSF) data from Terra to calculate the SWARF over the global oceans. To convert the measured radiances to TOA fluxes, we use empirically derived ADM's (Zhang et al., submitted manuscript, 2004a) and account for sample biases and diurnal effects (J. Zhang et al., Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 2. Global and Seasonal distributions, submitted to *Journal of Geophysical Research*, 2004b, hereinafter referred to as Zhang et al., submitted manuscript, 2004b). Furthermore, we examine the relationship between CERES shortwave flux and η as a function of AOT to examine the potential for using broadband CERES fluxes for obtaining anthropogenic aerosol climate forcing.

[10] Figure 1a shows the spatial distribution of SWARF over the global oceans derived from the time of the Terra satellite overpass and is therefore called instantaneous radiative forcing. Also superimposed on the figure are the zonal and meridional distributions of SWARF. Several features are clearly seen including the high SWARF values off the east coast of China, India and West coast of Africa with slightly smaller values off the North American continent. Dust aerosols from China are often transported across the Pacific Ocean to the West coast of the United States and the dust aerosols from Sahara is also transported across the Atlantic to the Eastern portion of the United States and South America [*Prospero et al.*, 2002]. South of the equator, during the dry season, biomass-burning activities from Africa are the primary reason for the SWARF distribution that is seen over the Atlantic Ocean. The influence of the roaring 40's and the associated high concentration of marine sea-salt aerosols above the maritime background are responsible for the high SWARF values in the Southern hemisphere. Our results also show that the SWARF over the Northern hemisphere is 1.5 times higher (-7.9 $\mathrm{Wm^{-2}}$)

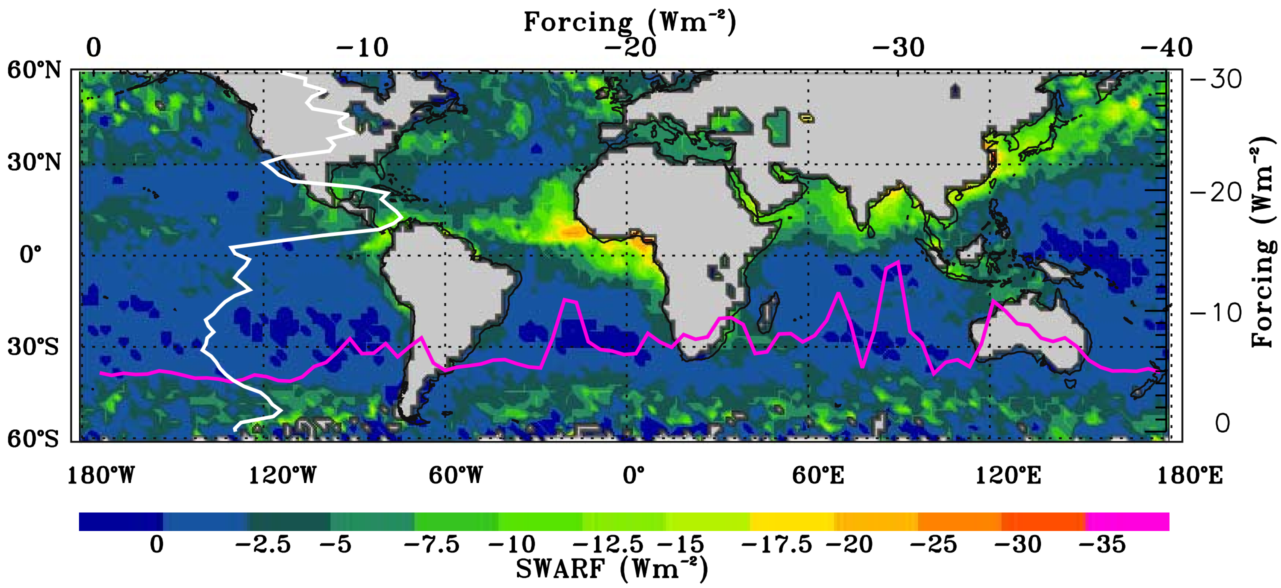

Figure 1a. Spatial distribution of instantaneous shortwave aerosol radiative forcing over cloud free regions for ten months (Nov 2000–Aug 2001). Also shown are the zonal and meridional distributions of SWARF with corresponding axis on the right and top of the figure.

when compared to the Southern hemisphere (−5.3 Wm^{-2}) that is consistent with previous broadband radiation budget studies derived from the Tropical Rainfall Measuring Mission (TRMM) [*Loeb and Kato*, 2002].

[11] The global mean instantaneous SWARF is −6.4 Wm^{-2} and the corresponding MODIS AOT at 0.55 μm ($\tau_{0.55}$) for the cloud-free CERES pixels is 0.09. However note that the MODIS retrieved $\tau_{0.55}$ that is at a higher spatial resolution when compared to the CERES is 0.15. Correcting for these sample biases between the MODIS and CERES using the radiative forcing efficiency of 70 Wm^{-2}/$\tau_{0.55}$ (Zhang et al., submitted manuscript, 2004b) and by assuming that the Terra-retrieved AOT is representative of the diurnally averaged values [*Kaufman et al.*, 2000], we estimate the cloud free direct aerosol radiative effect to be −5.3 Wm^{-2} (Zhang et al., submitted manuscript, 2004b). This value is within the range reported by previous studies (−5.5 Wm^{-2} [*Boucher and Tanré*, 2000]; −5.4 Wm^{-2} [*Chou et al.*, 2002]; −4.6 Wm^{-2} [*Yu et al.*, 2004]; −6.7 Wm^{-2} [*Haywood et al.*, 1999]). The uncertainties in our analysis are largely from measurements, Angular Dependence Models (ADM's) and clear-sky flux values and we estimate the combined uncertainty to be on the order of 1.7 Wm^{-2} (Zhang et al., submitted manuscript, 2004b).

[12] Figure 1b shows the relationship between CERES SW flux and MODIS derived η for selected regions (North Africa for dust, South Africa/Central America for biomass burning, North America/India for pollutant aerosols and Central Pacific for maritime aerosols) dominated by dust aerosols (in green), biomass burning/pollution (in red) and marine aerosols (in blue) for cosine of solar zenith ranges between 0.8–1.0. The $\tau_{0.55}$ ranges for marine aerosols are <0.06 and for dust and anthropogenic aerosols are >0.1. The mean $\tau_{0.55}$, η, and CERES SW flux are 0.24, 0.6 and 92 Wm^{-2} for dust, 0.21, 0.84, 89 Wm^{-2} for anthropogenic aerosols and 0.04, 0.58 and 77 Wm^{-2} for marine aerosol. Note that $\tau_{0.55}$ and η are derived from narrowband spectral measurements whereas the CERES SW flux are reported for broadband measurements. There is reasonable separation among the three "classes" that are shown in Figure 1b with some overlaps as expected. For small values of $\tau_{0.55}$ (marine aerosols) even slight uncertainties in AOT will induce large errors in η calculations due to the low sensitivity of MODIS retrieval algorithms for low aerosol loading. However, for larger AOT values there is a good

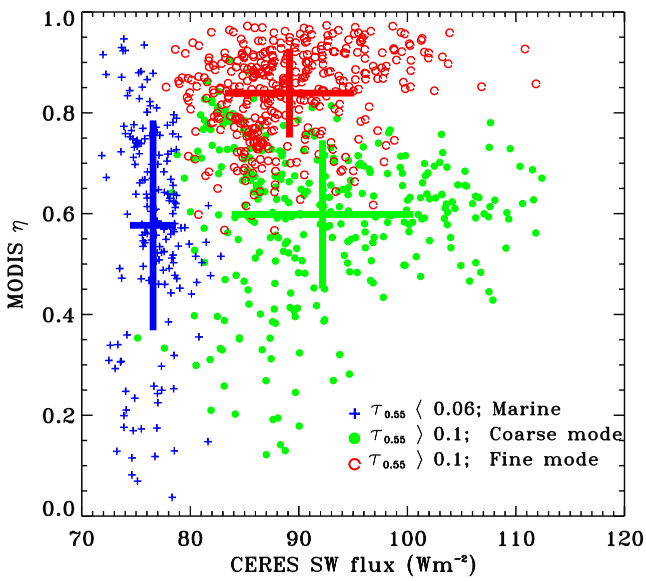

Figure 1b. Relationship between CERES shortwave flux and MODIS derived η for fine mode/anthropogenic (red), coarse mode/dust (green) and marine components (blue) for selected regions. The mean and standard deviation are indicated by the cross marks.

separation between regions dominated by dust aerosols and biomass burning/industrial pollution. Large η values over oceans are usually dominated by fine mode aerosols whereas dust aerosols on the other hand have smaller η values due to their large sizes [*Kaufman et al.*, 2002]. This separation of aerosol type by η provides a framework for further research to quantitatively study the role of anthropogenic aerosols on climate.

[13] One strategy for estimating the anthropogenic SWARF over cloud-free oceans will be to first remove cloud contamination from the CERES footprints using MODIS data, followed by separation of the marine background component using MODIS and AERONET derived optical thickness and near-surface ocean wind speed information. The optical depth of marine aerosol could be estimated as a function of near surface wind speed [*Kaufman et al.*, 2004], and the flux contributions from maritime aerosols will be obtained using CERES pixels observed over remote clear ocean regions (as flagged by $\tau_{0.55}$). Once the marine component is separated, the anthropogenic and natural components could be separated by using appropriate thresholds in η [*Kaufman et al.*, 2004]. Regional studies over major aerosol polluted regions will be used to estimate the variations in aerosol forcing efficiencies for various types of aerosols. This strategy can then be used for obtaining anthropogenic aerosol radiative forcing over the global oceans. However sensitivity of the anthropogenic SWARF to cloud contamination, $\tau_{0.55}$ and η thresholds must be examined.

3. Conclusions

[14] Using ten months of the CERES SSF product we have calculated the diurnally averaged cloud-free SWARF to be -5.3 ± 1.7 Wm^{-2}. Our calculations are largely a measurement based assessment and we do not invoke radiative transfer calculations to convert the satellite-retrieved AOT into TOA fluxes and SWARF. Although the life time of tropospheric aerosols is much smaller when compared to greenhouse gases such as carbon dioxide, aerosols due to their inhomogeneous spatial distribution and radiative properties, exert large latitudinal and longitudinal gradients in the amount of solar radiation reflected and absorbed by the surface and atmosphere. This could have important implications for dynamics of general circulation, hydrology and other processes [*Ramanathan et al.*, 2001]. We also partition the AOT and shortwave fluxes as a function of the ratio of fine mode fraction to the total aerosol optical (η) and conclude that it is an important parameter that has the potential for separating the effect of natural from anthropogenic aerosols from Terra and Aqua satellite measurements that is a subject of future research.

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